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Use Of Variation Merging Equations To Aid Implementation Of Accuracy Control

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ABSTRACT

Implementation of accuracy control in U. S. shipyards has encountered a number of impediments. These include the short run nature of shipbuilding, the difficulty in understanding the specifics of data collection, and the difficulty in prioritizing data collection efforts. As a part of it s return to new construction, with the building of three new Jumbo Mark II Ferries for the State of Washington, Todd Pacific Shipyards was hoping to implement accuracy control. This paper reports on a new approach to the use of variation merging equations as a means of prioritizing data collection efforts. The research, performed by University of Washington researchers in conjunction with Todd personnel, was successful in helping prioritize efforts to improve implementation of accuracy control.

INTRODUCTION

A recent study comparing U.S. shipbuilding practice to best international practice identifies a number of major areas of deficiency. Included in these is the application of the principles of Total Quality Management (TQM) [1]. A part of TQM applied to production involves the capability to efficiently control accuracy of interim products at each stage of construction. The goal of the research reported in this paper is to aid implementation of an accuracy control system that will enable a shipyard to control accuracy of interim products at each stage of construction, so that the amount of rework at the erection stage is decreased. Furthermore, the methodology developed in this research will enable the shipyard to predict the probability of rework at erection, which will in turn be beneficial to production planning and scheduling. Thus, the aim of this research is to assist in the development and implementation of a short run Statistical Process Control (SPC) system at a shipyard.

In order to fulfill the goal of this research, a construction project for the initiation of the system is required. That opportunity is provided by the Washington State Ferries (WSF) construction program awarded to Todd. The program initially involves the construction of three new Jumbo Mark II Ferries.

BASIC CONCEPT

A mature accuracy control system maintains and uses a substantial data base. Often, shipyards faced with implementation of a new accuracy control system, have difficulty in facing the enormous data collection and analysis effort required. Short term goals tend to preclude the completion of the time consuming data collection process. Thus, the long term needs of an accuracy control system are not satisfied.

An alternative to performing the data collection effort as a major undertaking is therefore employed. Shipyards prioritize processes for beginning data collection, with the goal being to incrementally develop the full data base required. Here again, many shipyards lose the will to complete this effort, and never fully achieve an accuracy control system. A key decision in any incremental approach to data base development is how to prioritize processes for initial data collection efforts. The common approach has been to employ the advice of consultants, or use in-house experience to make this choice.

The goal of this research is to test an alternative concept. The approach is to write variation merging equations using symbols for all variations, and use these equations to identify critical points and dimensions, as well as critical processes. Based on this, accuracy control planners have a better understanding of the priorities for data collection. Figure 1 shows this new concept.

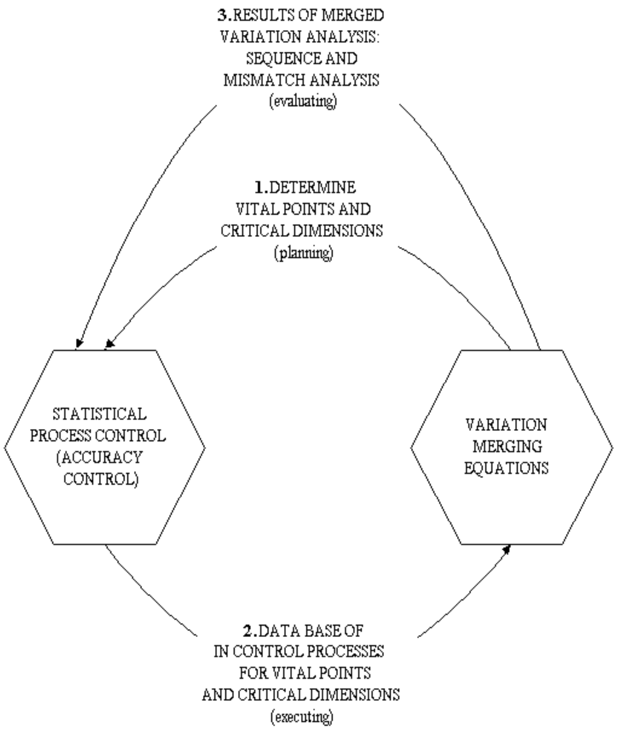


FIGURE 1 Relationship Between Variation Merging Equation and Statistical Process Control.

Figure 1 Relationship of Variation Merging Equations and the Accuracy Control System

STRUCTURAL SECTION

In order to test the concept of using variation merging equations to aid the development and implementation of a short run Statistical Process Control (SPC) system, or an accuracy control system, a project and specific structural section are chosen. The construction of three new ferries for the State of Washington provides the project on which to begin implementation of this short run SPC system. To simplify program implementation, concentration is only on structural work, omitting the outfitting work.

Figure 2 shows an outboard profile of the Jumbo Mark II ferry, detailing the block (unit) breakdown. Unit 107, an engine room unit, is taken as the starting point for developing the variation merging equations (see Figure 3). In spite of the difficulties in developing the variation merging equations for such a complex unit as unit 107, the benefits emerge during the generalization of the variation merging equations. Even though the variation merging equations are developed only for unit 107, it is an adequate example for establishing the guidelines for determining the vital points and critical dimensions, as well as critical processes at each stage. Furthermore, as will be pointed out later, the adaptation of the variation merging equations for other units requires little effort, compared to the effort required for developing the first series of variation merging equations.

This variation merging analysis provides the framework for the analysis of hull merged variations at the block (unit) assembly stage of construction. Once the data becomes available, results of this analysis can be used directly to perform assembly sequencing analysis, and mismatch analysis.

SHORT RUN STATISTICAL PROCESS CONTROL

Historically, control charting is applied in manufacturing where a large number of identical parts are being produced. With the general trend toward product customization, batch sizes are significantly reduced, sometimes even to one. Furthermore, Just-in-Time (JIT) manufacturing also causes a need for decreasing batch size, because this pull system means that the amount of production is driven by the immediate need for final assembly [2]. Consequently, the short run control chart was developed and is in common use for these situations.

Applying the principal of $\overline{X} - R$ control charts to short run production, the measured quality characteristic is replaced by deviation from nominal. This can be expressed in the form of the following equation:

$$x_{i,w} = M_{i,w} - N_w \ , \qquad (1)$$

where

$M_{i,w} =$ the *i* th actual sample measurement of the quality characteristic of *w*,
$N_w =$ the nominal value of the quality characteristic of *w*, and
$x_{i,w} =$ the deviation of the actual measurement from nominal of the *i* th sample of the quality characteristic *w*.

Then, the principal of standard $\overline{X} - R$ control charts is utilized. [3]

Furthermore, in the case where the measurement sample size is one, the ideas of short run process control can be combined with the principal of $\overline{X} - MR$ control charts, resulting in the short run $\overline{X} - MR$ control chart. This was used to sample and analyze data from a

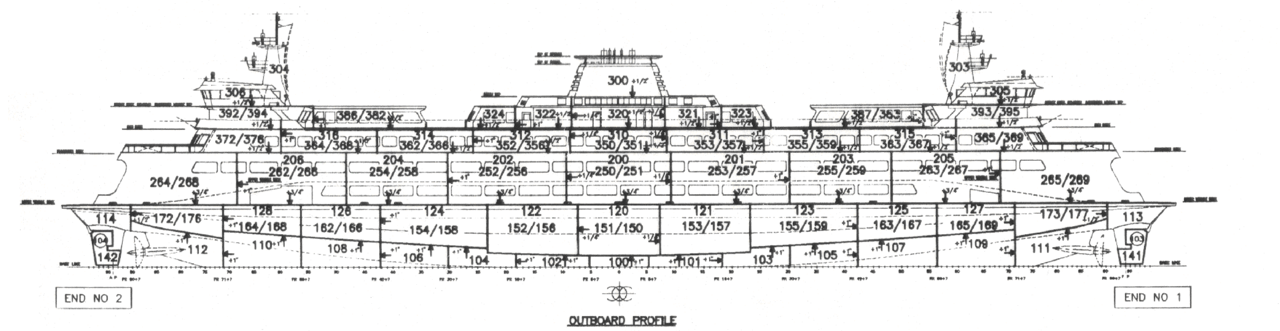


Figure 2 Outboard Profile of Jumbo Mark II Ferry Showing Block Breakdown

numerical control (N/C) cutting machine. Figure 4 shows the application of the short run $\overline{X} - MR$ control chart to the N/C cutting process (the data were acquired by accuracy control personnel at the shipyard).

DEVELOPING THE VARIATION MERGING EQUATIONS

At any stage of construction, variations can be classified into two types, the variations associated with the input components, and the variations introduced by the joining process. Thus, the basic information necessary to develop the variation merging equations for unit 107 includes:

- structural geometry of unit 107,
- structural geometry of the components of unit 107, and
- assembly procedures used in fabricating unit 107.

The assembly sequence actually employed for unit 107 results in inconsistencies in the merged variations to the interim products at the unit assembly level. For this reason, a specific and repeatable assembly sequence is used in the development of the variation merging equations. The details of the new assembly sequence are discussed in the next section.

Figure 3 is a sketch of the half-breath or cross sectional view of unit 107. The design of unit 107, as well as other units in this ferry, prevents significant merged variation in the longitudinal direction, by having very few longitudinal joints. The same is not the case in the transverse direction. The merged variations in the transverse direction are far more significant than those in the longitudinal direction. This situation is confirmed by the accuracy control personnel at the shipyard. As a result, the variation merging equations are developed in the transverse direction, instead of the longitudinal direction, as is the more conventional application of variation merging equations. This is also evident when considering that the scope of this work is focused on merged variations at unit assembly.

Assumptions Used In Variation Merging Equations

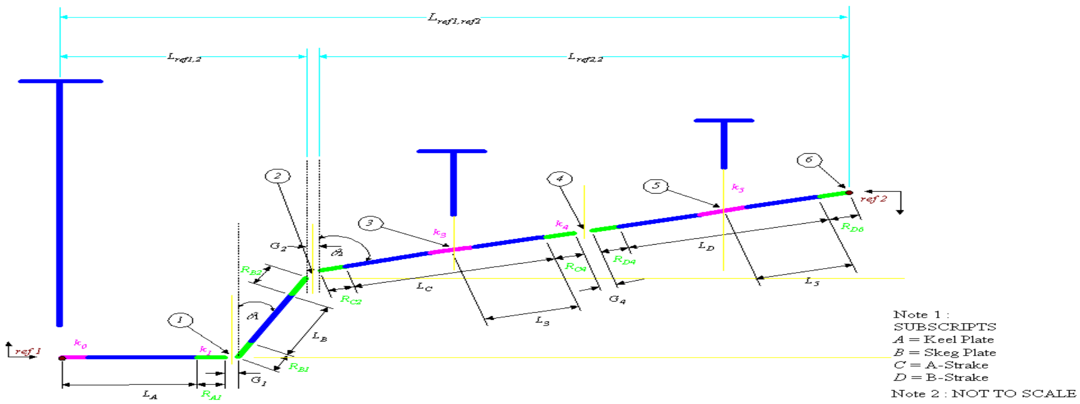
A uniform assembly sequence for unit 107 is chosen and is shown in Figure 5. As is shown in Figure 3, unit 107 is divided into two sub-units. Sub-unit 1 contains plates A and B, and sub-unit 2 contains plates C and D. Sub-unit 1 is assembled on the flat ground and then loaded onto a pin jig during the unit assembly stage. Sub-unit 1 is set on the pin jig with reference to *ref 1*. Sub-unit 2 is assembled on the pin jig with reference to *ref 2* (see Figures 3 and 5). Finally, both sub-units are joined at weld joint #2.

Apart from the general assumptions of rectangularity and flatness that must be made, an additional assumption is needed to facilitate the development of the variation merging equations. This additional assumption is that weld shrinkage is equally distributed about the weld seam. The logic of this assumption is based on the fact that both components are made from the equal thickness plates.

It is only at weld joint #1, between the keel plate and the skeg plate, or plate A and plate B in Figure 3, that the thickness between the two plates is different. The welding shrinkage is assumed to be directly dependent on the thickness of the plate, or $\text{Shrinkage} \propto (\text{Thickness})^{-1}$.

Variables In The Variation Merging Equations

Figure 3, a sketch of unit 107, provides the notation used to define the variables used in the



Weld joint

(1) indicates weld joint #1

(2) indicates weld joint #2

(3) indicates weld joint #3 (vertical)

(4) indicates weld joint #4

(5) indicates weld joint #5 (vertical)

(6) indicates weld joint #6 (Block weld joint)

Vital distance

$\mathbf{L}_{11} = \mathbf{L}_{\mathbf{ref}1,1}$ = Distance between reference point #1 (*ref* 1) and weld joint #1

$\mathbf{L}_{12} = \mathbf{L}_{\mathbf{ref}1,2}$ = Distance between reference point #1 (*ref* 1) and weld joint #2

$\mathbf{L}_{13} = \mathbf{L}_{\mathbf{ref}1,3}$ = Distance between reference point #2 (*ref* 1) and weld joint #2

$\mathbf{L}_{14} = \mathbf{L}_{\mathbf{ref}1,4}$ = Distance between reference point #2 (*ref* 2) and weld joint #3

$\mathbf{L}_{15} = \mathbf{L}_{\mathbf{ref}1,5}$ = Distance between reference point #2 (*ref* 2) and weld joint #5

Reference line

$\mathbf{R}_{\mathbf{A}1}$ = Distance between plate edge and reference line at end #1 of plate A

$\mathbf{R}_{\mathbf{B}1}$ = Distance between plate edge and reference line at end #1 of plate B

$\mathbf{R}_{\mathbf{B}2}$ = Distance between plate edge and reference line at end #2 of plate B

$\mathbf{R}_{\mathbf{C}2}$ = Distance between plate edge and reference line at end #2 of plate C

$\mathbf{R}_{\mathbf{C}4}$ = Distance between plate edge and reference line at end #4 of plate C

$\mathbf{R}_{\mathbf{D}4}$ = Distance between plate edge and reference line at end #4 of plate D

$\mathbf{R}_{\mathbf{D}6}$ = Distance between plate edge and reference line at end #6 of plate D

Weld gap

$\mathbf{G}_1$ = Weld gap at point #1

$\mathbf{G}_2$ = Weld gap at point #2

$\mathbf{G}_4$ = Weld gap at point #4

Shrinkage

$\mathbf{k}_0$ = Shrinkage due to CVK fillet weld at *ref* 1

$\mathbf{k}_1$ = Shrinkage due to butt weld at point #1; keel plate & skeg plate joining

$\mathbf{k}_1^{/}$: assume $\text{Shrinkage} \propto (\text{Thickness})^{-1}$

$\mathbf{k}_2$ = Shrinkage due to butt weld at point #2; skeg plate & A-strake joining

$\mathbf{k}_2^{/} = \frac{\mathbf{k}_2}{2}$: assume equal heat distribution about welding point

$\mathbf{k}_3$ = Shrinkage due to girder fillet weld at point #3; on A-strake

$\mathbf{k}_3^{/} = \frac{\mathbf{k}_3}{2}$: assume equal heat distribution about welding point

$\mathbf{k}_4$ = Shrinkage due to butt weld at point #2; A-strake & B-strake joining

$\mathbf{k}_5$ = Shrinkage due to girder fillet weld at point #5; on B-strake

$\mathbf{k}_5^{/} = \frac{\mathbf{k}_5}{2}$: assume equal heat distribution about welding point

Note: Welding shrinkage is a natural negative variable. For example, if the measured shrinkage is 3/16 in., it would appear in the equation as -3/16 in..

Length of plate

$\mathbf{L}_\mathbf{A}$ = Length (between reference lines) of plate A

$\mathbf{L}_\mathbf{B}$ = Length (between reference lines) of plate B

$\mathbf{L}_\mathbf{C}$ = Length (between reference lines) of plate C

$\mathbf{L}_\mathbf{D}$ = Length (between reference lines) of plate D

$\mathbf{L}_3$ = Length between reference line at end #4 and girder at point #3

$\mathbf{L}_5$ = Length between reference line at end #6 and girder at point #5

Angle

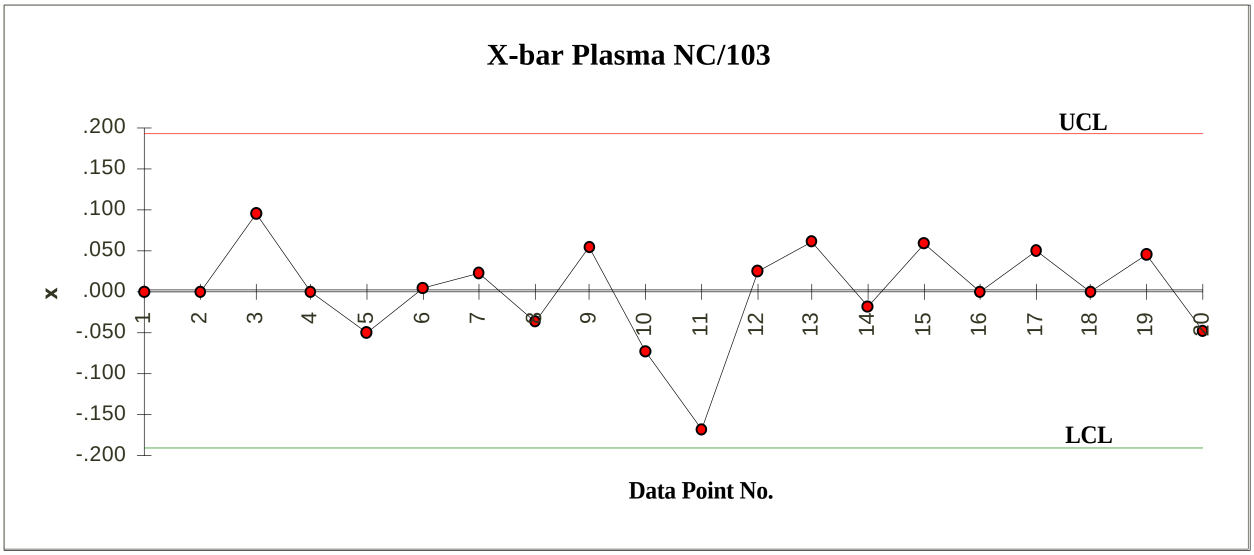
θ_1 = Angle of plate B reference to vertical plane

θ_2 = Angle of plate C and D (subassembly C&D) reference to vertical plane

Figure 3 Section View of Unit 107

$\overline{X} - MR$ Control Chart Plot

Hull No. : M7091		Project : WSF	
Unit No. : 103		Date : xx/xx/xx	
Process : Plasma NC Cutting		Stage of Construction : Part Fabrication Stage	
By : John D.		Measurement Description : Cutting dimension from plasma NC machine	
NOTE :	*Sample Size; n = 1*		
	Number of Sample; m = 20		



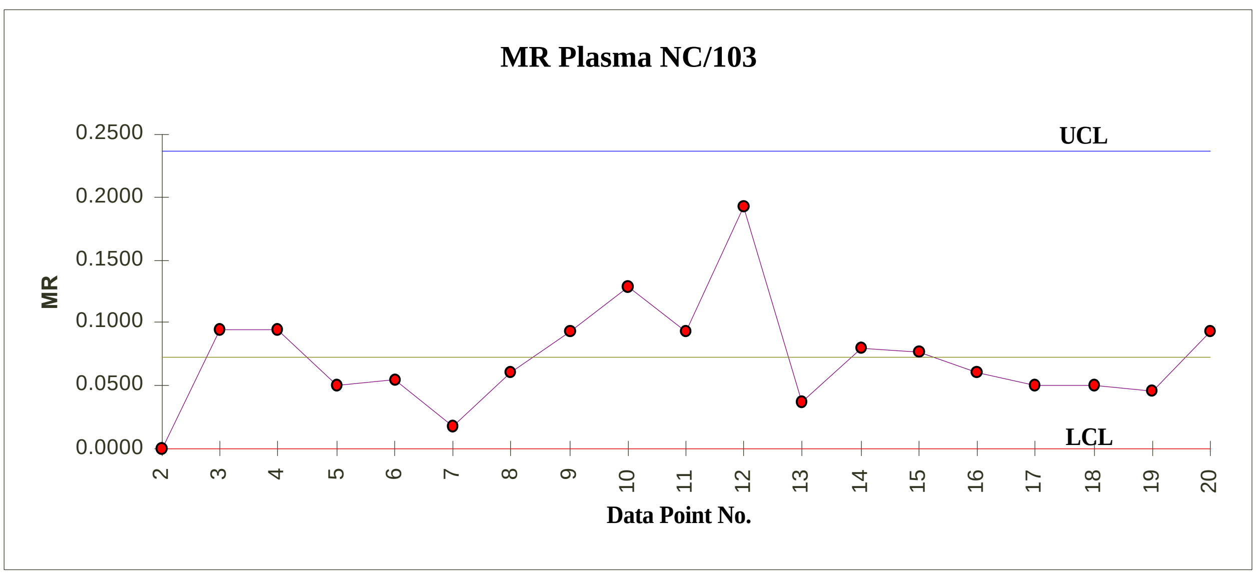


Figure 4 X - MR Control Chart

variation merging equations. The variables refer to both dimensions and measuring methods, as follows.

- L_{nn} denotes the distance from the reference point #*n* to the weld joint #n. The data for this variable is collected at the assembly stage.
- k_n denotes the weld shrinkage at weld seam #*n*. There are 3 types of weld joints: butt weld, angular butt weld, and fillet weld. Each type is subject to different shrinkage amounts. Besides the type of weld, other attributes, including weld gap, type of material, thickness of material, type of edge (i.e., bevel), and welding parameters (heat and voltage) must also be considered.
- L_X and L_n are variables denoting the length between the reference lines. L_X denotes the distance between plate reference lines whereas L_n denotes the distance between the plate reference line and the fillet weld joint reference line. The data for these variables are obtained at the parts fabrication stage.
- R_{Xn} denotes the distance between the reference line and the plate edge at the same end of plate *X*. The data for this variable is also obtained at the parts fabrication stage.
- G_n denotes the width of the weld gap at weld seam #n provided by the fitter. The data for this variable is obtained by measuring the weld gap before welding at the fitting process.
- θ_n denotes the angle of the subassemblies #*n*. The data for this variable is obtained by measuring the elevation and the horizontal dimension of the subassembly, and calculating the inclining angle in reference to the vertical plane. While θ_1 is dependent on the assembly process, θ_2 is determined by the pin jig setting process.

Variation Merging Equations

The variation merging equations developed in this section follow the standard approach, as described in [4]. The equations include the geometric equation, and the variation and variance merging equations. These equations are based on predicting the merged variation at weld joint 2. The resulting geometric equation, variation merging equation and variance merging equation of G_2 are presented as follows.

Geometric Equation:

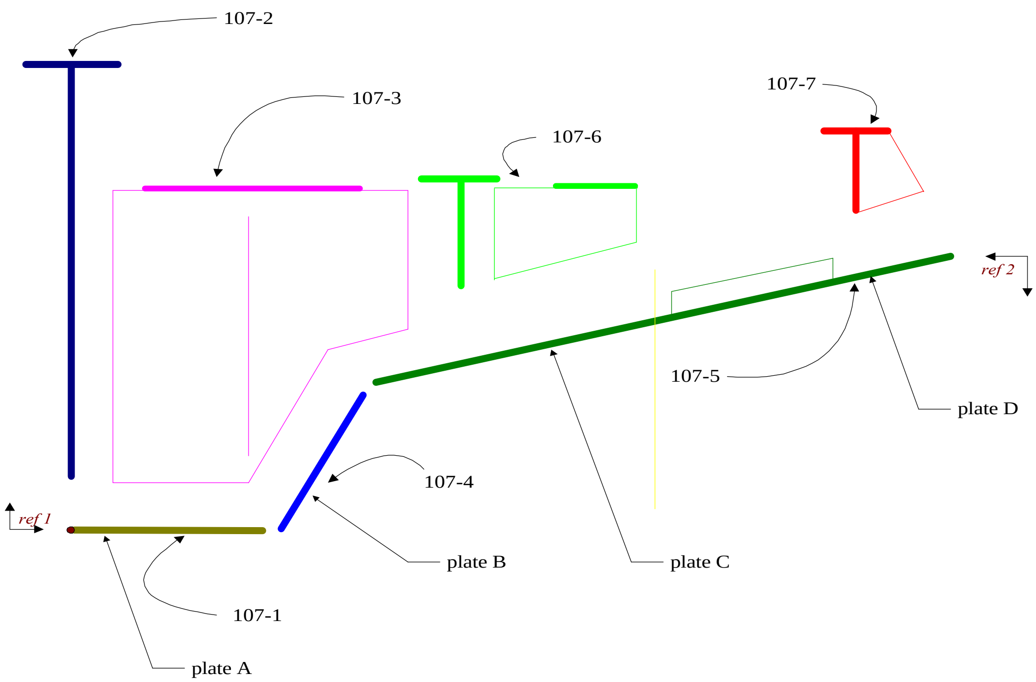
$$G_2 = L_{ref\,1,ref\,2} - (L_{12} + L_{22}) \qquad (2)$$

Variation Equation:

$$\begin{aligned}
\overline{X_{G_2}} = \overline{\delta L_{ref\,1,ref\,2}} - \{[\overline{\delta k_0} + \overline{\delta L_A} + \overline{\delta R_{A1}} + \overline{\delta k_1} + \overline{\delta G_1} \\
+ [(R_{B1} + \overline{\delta R_{B1}}) * Sin(\theta_1 + \overline{\delta\theta_1}) - R_{B1} * Sin\theta_1] \\
+ [(L_B + \overline{\delta L_B}) * Sin(\theta_1 + \overline{\delta\theta_1}) - L_B * Sin\theta_1] \\
+ [(R_{B2} + \overline{\delta R_{B2}}) * Sin(\theta_1 + \overline{\delta\theta_1}) - R_{B2} * Sin\theta_1] \\
+ [(k_2^{/} + \overline{\delta k_2^{/}}) * Sin(\theta_1 + \overline{\delta\theta_1}) - k_2^{/} * Sin\theta_1]\} \\
- \{[(R_{D6} + \overline{\delta R_{D6}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{D6} * Sin\theta_2] \\
+ [(k_5 + \overline{\delta k_5}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_5 * Sin\theta_2] \\
+ [(L_D + \overline{\delta L_D}) * Sin(\theta_2 + \overline{\delta\theta_2}) - L_D * Sin\theta_2] \\
+ [(R_{D4} + \overline{\delta R_{D4}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{D4} * Sin\theta_2] \\
+ [(k_4 + \overline{\delta k_4}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_4 * Sin\theta_2] \\
+ [(G_4 + \overline{\delta G_4}) * Sin(\theta_2 + \overline{\delta\theta_2}) - G_4 * Sin\theta_2] \\
+ [(R_{C4} + \overline{\delta R_{C4}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{C4} * Sin\theta_2] \\
+ [(k_3 + \overline{\delta k_3}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_3 * Sin\theta_2] \\
+ [(L_C + \overline{\delta L_C}) * Sin(\theta_2 + \overline{\delta\theta_2}) - L_C * Sin\theta_2] \\
+ [(R_{C2} + \overline{\delta R_{C2}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - R_{C2} * Sin\theta_2] \\
+ [(k_2^{/} + \overline{\delta k_2^{/}}) * Sin(\theta_2 + \overline{\delta\theta_2}) - k_2^{/} * Sin\theta_2]\} \quad (3)
\end{aligned}$$

Variance Equation:

$$\begin{aligned}
S_{G_2}^2 = S_{L_{ref\,1,ref\,2}}^2 + (S_{k_0}^2 + S_{L_A}^2 + S_{R_{A1}}^2 + S_{k_1}^2 + S_{G_1}^2) \\
+ S_{G_4}^2 + S_{R_{C4}}^2 + S_{k_3}^2 + S_{L_C}^2 + S_{R_{C2}}^2 + S_{k_2^{/}}^2)]\} \\
+ \{[(R_{D6} + \overline{\delta R_{D6}}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S_{\theta_2}^2]\} \\
+ \{[(k_5 + \overline{\delta k_5}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S_{\theta_2}^2]\} \\
+ \{[(L_D + \overline{\delta L_D}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S_{\theta_2}^2]\} \\
+ \{[(R_{D4} + \overline{\delta R_{D4}}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S_{\theta_2}^2]\} \\
+ \{[(k_4 + \overline{\delta k_4}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S_{\theta_2}^2]\} \\
+ \{[(G_4 + \overline{\delta G_4}) * [Cos(\theta_2 + \overline{\delta\theta_2})]^2 * S_{\theta_2}^2]\}
\end{aligned}$$



SET REFERENCE POINT AT *ref 1*

JOIN CVK SUB-ASSY (107-2) TO KEEL PLATE (107-1)

JOIN FRAME #43-56 (107-3) AND LONG'L GIRDER TO SUB-UNIT (107-1-2)

JOIN SHELL PLATE (107-4) TO SUB-UNIT (107-1-2-3)

LOAD SUB-UNIT (107-1-2-3-4) ONTO PIN JIG

SET REFERENCE POINT AT *ref 2*

LOAD SHELL PLATE (107-5) ONTO PIN JIG AND JOIN ALL TRANSVERSE STIFFENER TO SHELL

JOIN LONG'L GIRDER SUB-ASSY (107-6) TO SUB-UNIT (107-5) ON PIN JIG

JOIN LONG'L GIRDER SUB-ASSY (107-7) TO SUB-UNIT (107-5-6) ON PIN JIG

JOIN SUB-UNIT 1 (107-1-2-3-4) TO SUB-UNIT 2 (107-5-6-7) AT MAIN SUB-UNIT JOINT

<u>Figure 5</u> Initial Assembly Sequence of Unit 107

1	2	3	4	5	6	7
PRODUCTION STAGE	PROCESS	VARIABLE GROUP	VARIABLE SUBGROUP	VARIABLE - UNIT 107	MEASUREMENT DESCRIPTION	MEASURING TOOL
Parts Fabrication	NC Cutting - 3/4" mild steel	δL	(δL *- 3/4 - ms*)	δL_A	Distance between reference line	Measuring Tape
	NC Cutting - 7/16" mild steel	δL	(δL *- 7/16 - ms*)	δL_B , δL_C , δL_D	Distance between reference line	Measuring Tape
	NC Marking - mild steel	δR	(δR *- ms*)	δR_{A1} , δR_{B1} , δR_{B2} , δR_{C2} , δR_{C4} , δR_{D4} , δR_{D6} .	Distance between plate edge and punch mark reference line	1/32" - Ruler
	NC Marking - X	δR	(δR *- X*)	N/A	Distance between plate edge and punch mark reference line	1/32" - Ruler
	Ink Marking	δR	(δR *- ink*)	N/A	Distance between plate edge and punch mark reference line	1/32" - Ruler
Sub-Unit/Sub-Block Assembly	Fitting - angle joint between 3/4" and 7/16" mild steel plate	δG	(δG *- a - 3/4 & 7/16 - ms*)	δG_1	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/32" - Ruler
	Fitting - butt joint between 7/16" and 7/16" mild steel plate	δG	(δG *- b - 7/16 - ms*)	δG_4	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/32" - Ruler
	Fitting - other types of joints used in other units	δG	(δG *- x - nnn - X*)	N/A	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/32" - Ruler
	Welding - Fillet weld between CVK and keel plate	δk	(δk *- f - CVK & Kplt*)	δk_0	Welding shrinkage - measure difference in distance between reference lines before and after weld	1/32" - Ruler
	Welding - Butt weld between 7/16 " and 7/16" mild steel plate	δk	(δk *- b - 7/16 - ms*)	δk_4	Welding shrinkage - measure difference in distance between reference lines before and after weld	1/32" - Ruler
	Welding - Fillet weld between 7/16 " and 7/16" mild steel plate	δk	(δk *- f - 7/16 - ms*)	δk_3 , δk_5	Welding shrinkage - measure difference in distance between reference lines before and after weld	1/32" - Ruler
Unit Assembly	Reference Point Setting	$\delta L_{ref1,ref2}$	-	$\delta L_{ref1,ref2}$	Distance between set reference point for pin jig assembly	Measuring Tape
	Fitting - angle joint between 7/16" and 7/16" mild steel plate (on jig)*	δG	(δG *- a - 7/16 - ms*) - on jig	δG_2	Distance between reference line on each plate, subtracting distance between plate edge and reference line -Fitting weld gap width	1/16" - Ruler
	Pin Jig Angle Setting	$\delta\theta$	-	$\delta\theta_1$, $\delta\theta_2$	Angle setting - measuring height and width of right triangle formed by angle, then calculate angle by trigonometry	Measuring Tape

* indirect measurement is taken.

TABLE 1 Summary of Vital Points and Critical Dimensions

$$+\{[(R_{C4}+\overline{\delta R_{C4}})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(k_3+\overline{\delta k_3})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(L_C+\overline{\delta L_C})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(R_{C2}+\overline{\delta R_{C2}})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\}$$
$$+\{[(k_2^{/}+\overline{\delta k_2^{/}})*[\mathrm{Cos}(\theta_2+\overline{\delta\theta_2})]^2 * S^2_{\theta_2}]\} \quad (4)$$

The geometric equation, equation (2), expresses the variations associated with the components and the variations that are introduced by the joining process at the unit assembly stage. This geometric equation is simply derived from the physical location of points under consideration. Next, the variation equation, equation (3), takes into consideration only the deviation from the nominal dimensions of each variable present in the geometric equation. Lastly, in the variance equation, equation (4), the variance of weld gap G_2 is determined by combining the variances of sub-unit 1, sub-unit 2, and the variances of joining processes.

PRIORITIZING DATA BASE DEVELOPMENT

All variables appearing in equations (2), (3) and (4) must be measured by production. However, by applying the principals of short run SPC, the variables can be classified into groups, which will in turn dictate a measurement plan. The categorization criteria are the similarities of the attributes of the variables and the sources of the variations. The results of the categorization are shown in Table I.

Referring to Table I, the variables are grouped by the measurement method (column 6) and the stage of construction (column 1). As a result, the variable group (column 3) for each stage of construction is determined. Then, within each group, the variables are subdivided into subgroups according to the characteristics of the processes that are the sources of variations (column 2). For example, the variables δL_A, δL_B, δL_C and δL_D belong to δL group, which are the measurement of distances between reference lines at the parts fabrication stage. Then, the δL group is subdivided into subgroups $(\delta L-3/4-\mathrm{ms})$ and $(\delta L-7/16-\mathrm{ms})$, because differences in plate thickness yield different patterns of variations. In Table I, δL_A falls into the $(\delta L-3/4-\mathrm{ms})$ subgroup while δL_B, δL_C and δL_D fall into the $(\delta L-7/16-\mathrm{ms})$ subgroup. Using the same idea, the rest of the variables appearing in equations (2), (3), and (4) are classified as shown in Table I.

Based on the vital points and critical dimensions, as summarized in Table I, the data collection and measurement methods must be planned. In the executing stage of the short run SPC system, control charts must be employed in order to achieve an in-control state, so the variation merging equations can be used to perform assembly sequence and mismatch analysis.

VARIATION MERGING EQUATION ANALYSES

After all vital points and critical dimensions are determined and sufficient data is collected, the variation merging equations can be used to calculate the probability of rework. Two types of rework analysis are considered, assembly sequencing analysis and mismatch analysis.

Assembly Sequencing Analysis

Inasmuch as assembly sequence is a major determinant of the merged variation at the weld gap G_2, assembly sequencing analysis is used to determine the best assembly sequence. The best assembly sequence is defined as the assembly sequence that yields the least deviation from the nominal design weld gap, as shown in Figure 6.

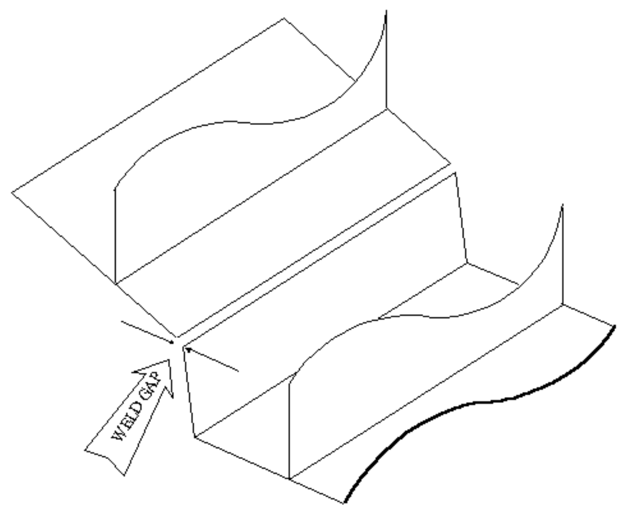


Figure 6 Weld Gap Location For Joining Assemblies

Using the series of variation merging equations developed for the merged variation at weld gap 2, the probability of rework can be predicted. First, with the data collected from production, the mean and the standard deviation (square root of variance) of weld gap variable G_2 can be computed. Then, the distribution of the weld gap G_2 can be generated, as shown in Figure 7. If tolerance limits of the weld gap G_2 are known, the percentage of rework can be computed from the constant *c* in the following equation:

$$\mathrm{Tolerance\_Limit} = (G_2 + \overline{X_{G_2}}) + cS_{G_2} \quad (5)$$

where

$\mathrm{Tolerance\_Limit}$ - known parameter from the standard tolerance; upper tolerance limit and lower tolerance limits,

G_2 - known design (nominal) dimension of weld gap #2,

$\overline{X_{G_2}}$ - known mean deviation of weld gap G_2 (from the database),

S_{G_2} - known standard deviation of weld gap G_2 (from the database), and

c - unknown normalizing constant determining the control limit.

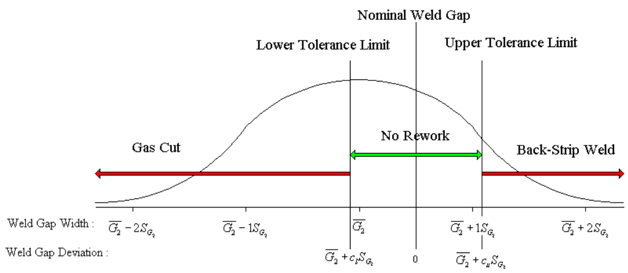


Figure 7 Weld Gap Distribution Showing Rework Regions

In equation (5), the value of variable c can be easily determined. Next, the area under the curve of the distribution of the weld gap G_2 can be determined by using any Gaussian probability distribution (standard normal) table. The percentage of gas cut can be calculated by substituting the lower tolerance limit of the weld gap into equation (5), and the percentage of back-strip welding can be calculated by substituting the upper tolerance limit of the weld gap into equation (5). In other words, if the weld gap is narrower than the smallest permissible gap width, the plate must be trimmed by gas cutting, and if the weld gap is wider than the largest permissible gap width, the back-strip welding process is used. In Figure 7, the shaded-arrow area in the middle section illustrates the no-rework region. Figure 7 is for illustrative purposes only, since the data base needed for this analysis is not yet available. In reality, the proportion of the no-rework region is expected to be much larger. Finally, by examining various assembly sequences, the best assembly sequence can be determined.

In addition to determining the best assembly sequence, the longer term solution can be obtained by linking the result of the analysis with the design. Maximizing the no-rework region can be accomplished by compensating for the variations due to the production process by adjusting dimensions during the design. Also, from the perspective of shipyard management, estimating the amount of rework in advance provides great value to planning and scheduling of production. Finally, from the perspective of process improvement, the results of the analysis can be used as a target for improving process capability.

Mismatch Analysis

Another use of the variation merging equations is to predict the probability that longitudinal bulkheads and girders of consecutive units line up within acceptable tolerances during erection. Figure 8 illustrates the alignment of the longitudinal girders. Mismatch of these longitudinal girders is potentially a major problem due to the structural implications of such a condition. Consequently, a mismatch requires an urgent schedule for rework, or the erection stage could become a bottleneck.

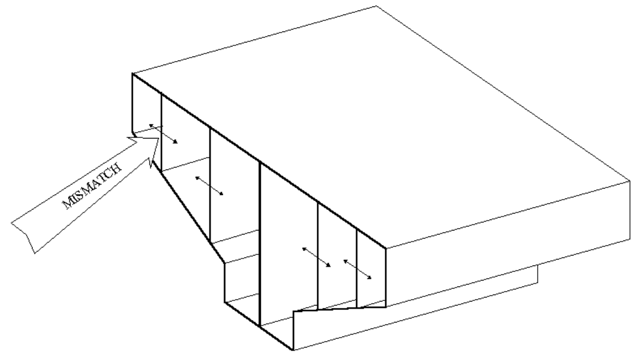


Figure 8 Longitudinal Girder Alignment

Essentially, two approaches can be used to correct this mismatch. If the mismatch is fairly small, the girders can be forced in place by using mechanical methods. However, if the mismatch exceeds the capability of mechanical restraints, the weld seam must be scarfed loose, readjusted, and re-welded.

For unit 107, points 1, 2, 3 and 5 (see Figure 3) are of interest in the mismatch analysis. Therefore, the corresponding variation merging equations are developed to express the pattern of merged variations at each of these points. Unlike the variation merging equations for the assembly sequencing analysis, these equations must take into consideration the variation along both the X-axis and the Y-axis. Otherwise, the form of the equations is identical to those shown previously (equations 2, 3, and 4). To save space, these equations are not presented here, but may be found in [5].

Like the assembly sequencing analysis, the probability of rework is also of interest. However, the mismatch analysis has two sets of tolerance limits, which are called the first- and second-tier tolerance limits (see Figure 9). If the mismatch is within the first-tier tolerance limits, no rework will be done; if the mismatch falls between the first-tier and the second tier tolerance limits (on the same side), mechanical methods need to be applied; if the mismatch falls beyond the second-tier tolerance limits, readjustment of the longitudinal girders is required.

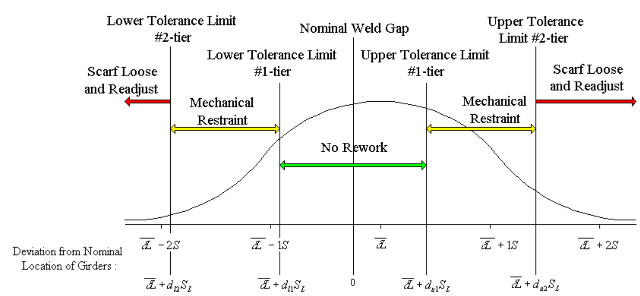


Figure 9 Mismatch Rework Analysis

As explained for the assembly sequencing analysis, the mismatch analysis requires data collected from production as well as the variation merging equations for each point of interest. Then, the distribution of the mismatch can be determined. Finally, the probability of rework can be computed by substituting the design tolerance limits, the merged variation, and the merged variance of each point of interest into the following equation:

$$Tolerance\_Limit = \overline{X_{nn}} + dS_{nn} \quad (6)$$

where

$Tolerance\_Limit$ - known parameter from the standard tolerance; lower tolerance limit and upper tolerance limit,

$\overline{X_{nn}}$ - mean deviation from the nominal of the location *n* reference to *ref n;*

S_{nn} - standard deviation of mismatch location of the location *n* reference to *ref n;* and

d - unknown normalizing constant determining the control limit.

The unknown constant *d* can be determined and the area under the curve in the range of interest can be obtained by consulting the Gaussian (standard normal) probability distribution. As a result, the percentage of each type of rework, at each vital point can be determined (see Figure 9).

Once the percentage of rework is predicted, insight into the process capability will be gained. As a consequence, a shipyard can confidently and effectively make the decision of when to implement corrective action. For example, if the results of the analysis show a the lack of process capability, the short-term solution can be to postpone the final welding until the erection stage, while the long-term solution may be to improve the fabrication process accuracy.

CONCLUSION

In implementing a short run SPC system (accuracy control system), the variation merging equation methodology is employed at two different stages, planning and evaluating. In detail planning, the variation merging equations are used to provide guidance in identifying the vital points and critical dimensions. As a result of the application of the variation merging equations to identify the vital points and critical dimensions, the initial process control effort can concentrate on critical processes that are the sources of variations in critical dimensions. In brief, the purpose of utilizing the variation merging equations at this stage of the system is to maximize the yield of the process control effort.

In the evaluating stage, after the processes are in control and sufficient data is available, the variation merging equations are used to perform assembly sequencing analysis and mismatch analysis. Despite the different purposes, both types of analysis are used to predict the probability of rework. Furthermore, these results can be fed back to the design stage so that the variations are properly accounted for by design dimensions. The final outputs of the analysis activities - including analysis of assembly sequence and analysis of mismatch - can be used to improve the process as well as to improve the design.

Variation merging equations are a powerful tool that can aid accuracy control efforts in a number of ways. This research has verified that the equations can help implement a new system, by prioritizing data base development efforts. They are also very powerful for process analysis and process improvement.

REFERENCES

1. Storch, R., Clark, J., and Lamb, T., "Technology Survey of U.S. Shipyards - 1994," *Journal of Ship Production*, Vol. 11, No. 3, August, 1995.
2. Alsup, F., and Watson, R., *Practical Statistical Process Control: A Tool for Quality Manufacturing,* Van Nostrand Reinhold, New York, 1993.
3. Montgomery, D., *Introduction to Statistical Quality Control,* John Wiley & Sons, New York, 1996.
4. Storch, R., "Accuracy Control Variation Merging Equations: A Case Study of Their Application in U.S. Shipyards," *Journal of Ship Production,* Vol. 1, No. 2, May, 1985.
5. Anutarasoti, S., *Short Run Statistical Process Control (SPC) System Development and Implementation in Shipbuilding*, Masters Thesis, University of Washington, 1996.

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